



Fermi National Accelerator Laboratory

Fermilab-Conf-93/056-T

April 14, 1993

OVERVIEW OF ACCELERATOR LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS ¹

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Abstract

There is renewed interest in performing a long baseline neutrino oscillation experiment using accelerator neutrinos because of a discrepancy between the measured and the predicted values of the ratio of electron to muon neutrinos produced in the upper atmosphere by cosmic rays. The approximate range in oscillation parameter space indicated by the Kamiokande atmospheric neutrino results and confirmed by IMB is bounded by $10^{-3} \text{ eV}^2 < \Delta m_0^2 < 10^{-1} \text{ eV}^2$ and $\sin^2 2\theta_0 > 0.4$. To reach such small Δm_0^2 , using an accelerator as the source of neutrinos where the energy is typically 1 GeV or greater, requires baselines in the range of 10 km to 1000 km. In this talk I will give an overview of the most likely possibilities for such a long baseline accelerator neutrino oscillation experiment.

¹Invited talk at the "Moriond Workshop on Neutrino Physics", January 30 to February 6, 1993 at Villars, Switzerland.



1 Introduction

The recent indications of a deficit in the ν_μ flux of atmospheric neutrinos and the long-standing solar neutrino problem have motivated new searches for neutrino oscillations with small neutrino Δm^2 . The results of the Kamiokande collaboration on atmospheric neutrinos suggest oscillation parameters in the range bounded by $10^{-3} \text{ eV}^2 < \Delta m_0^2 < 10^{-1} \text{ eV}^2$ and $\sin^2 2\theta_0 > 0.4$. This result has renewed interest in using accelerator neutrinos to perform a long baseline neutrino oscillation experiment. Many possibilities have been discussed; it is almost like picking an accelerator from column A and a detector from column B and there you have a possible experiment! In this overview I will brief review the range of parameter space a neutrino oscillation experiment can explore and then discuss the most likely possibilities.

The transition probability of producing one flavor of neutrino ν_a , of energy E , at the source, letting the neutrino propagate to the detector, a distance L away, and then detecting the neutrino as a different flavor ν_b , is (for a derivation see, for example, ref [1])

$$\mathcal{P}_{ab} = \sin^2 2\theta_0 \sin^2 \left(1.27 \frac{\Delta m_0^2 L}{E} \right) \quad (1.1)$$

where Δm_0^2 , E and L are measured in eV^2 , GeV , and km respectively. Δm_0^2 is the difference of the squares of the masses for the two neutrino mass eigenstates and θ_0 is the mixing angle relating these mass eigenstates to the flavor eigenstates. The experiments that measure this probability either measure a finite value for \mathcal{P}_{ab} or assign a limit $\mathcal{P}_{ab} < P_{min}$; the value of P_{min} , the energy spectrum of detected neutrinos and the source-detector distance then define a region in the $(\sin^2 2\theta_0, \Delta m_0^2)$ plane for each experiment. This P_{min} is the minimum measurable oscillation probability for the experiment in a given analysis mode. The size of P_{min} , or the limit in our ability to measure \mathcal{P}_{ab} , arises from many sources; statistical uncertainties, the contamination of the beam with other neutrino species, the fractional uncertainty in the neutrino flux calculations, the knowledge of the experimental acceptance for the different neutrino species, the backgrounds to the ν_b signal and many other systematic uncertainties.

For large $\Delta m_0^2 (\gg E/L)$ an experiment can explore any

$$\sin^2 2\theta_0 \geq 2 P_{min}. \quad (1.2)$$

For $\sin^2 2\theta_0 = 1$ the limit on the mass difference squared is

$$\Delta m_0^2 \geq \frac{\sqrt{P_{min}} E}{1.27 L}, \quad (1.3)$$

assuming $P_{min} \ll 1$. For smaller $\sin^2 2\theta_0$ a good *approximation* to the probability contour is a straight line with slope $-1/2$ in a log-log plot in the $(\sin^2 2\theta_0, \Delta m_0^2)$ plane until this line intersects the vertical line from Eq. 1.2.

Therefore, for the range indicated by the atmospheric neutrino data, an interesting experiment for this purpose will need to have a $P_{min} \approx 10\%$ or better and E/L at least one but preferable two orders of magnitude smaller than 0.4 GeV/km .

2 Fermilab - Soudan 2

The new Main Injector at Fermilab will be a 120 GeV proton accelerator that can deliver 2×10^{20} protons on target (POT) in a 10^7 sec-year . If a new neutrino beamline is constructed at Fermilab

for both a short baseline experiment. P803 [2], as well as for a long baseline experiment, using this accelerator as a source of protons, then the average energy of muon neutrinos produced would be approximately 10 GeV. The contamination from muon anti-neutrinos and electron neutrinos will be at the percent level. Initially there were three proposals for the long baseline detector: IMB, Soudan 2 and DUMAND. Since that time, IMB has ceased to exist and the engineering and environmental issues of sending a beam 30 degrees below the horizontal to DUMAND, make it prohibitively expensive.

Soudan 2 is 710 km from Fermilab in a direction 3.2 degrees below the horizontal [3]. This detector is a modular fine-grain tracking calorimeter with a mass of 1 kTon (with a possible upgrade to 5 kTon) surrounded on all sides by a two-layer active shield of proportional tubes. The analysis would be based on the ratio of events that appear in the far detector to be of neutral current type to that of charged current type compared to the same ratio in a near "identical" detector. The exclusion plots are shown in Fig.1. The difference in the limits between the two oscillation modes comes from the difference in the ν_τ charged current cross section compared to ν_e or ν_μ .

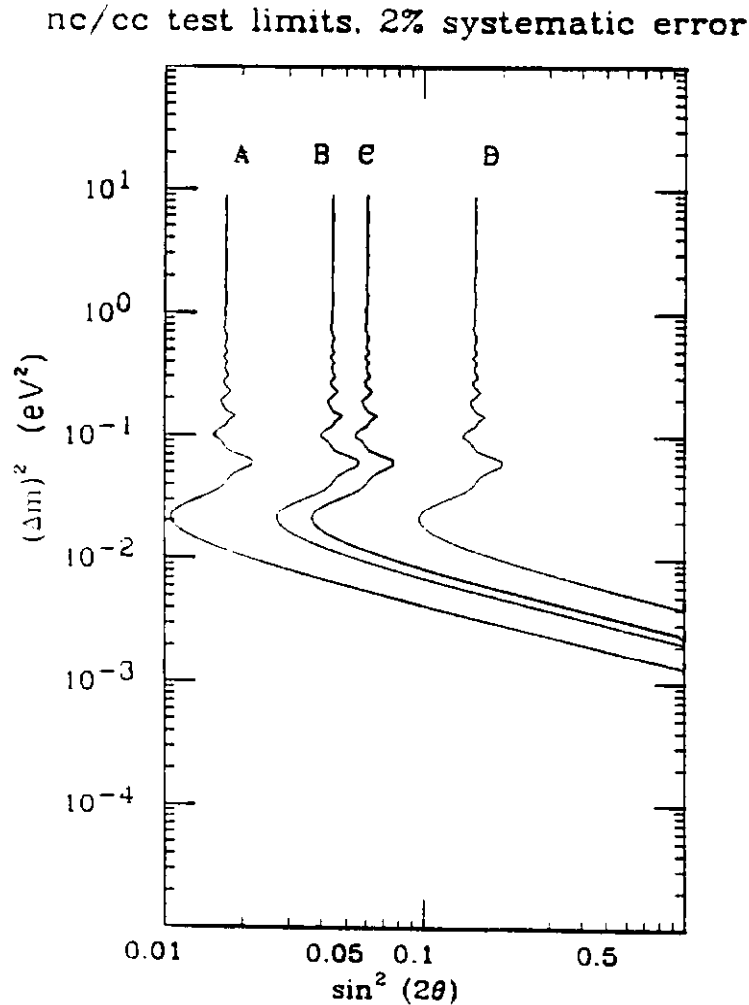


Figure 1: Fermilab/Soudan 2 90% CL limits: A and B are for a 4 year run and a 5 kTon fiducial volume detector (14k events) for $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$ respectively. C and D are for a 9 month run using only the current 0.9 kton (680 events) for $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$ respectively.

3 BNL - New Detector

Mann and Murtagh [4] have proposed a long baseline experiment using the BNL-AGS which can deliver 6×10^{13} POT every 1.7 sec, thus achieving 2×10^{20} POT in 100 days. The average neutrino energy is approximately 1 GeV and the contamination from ν_e is about 1%. A new neutrino beamline will need to be constructed for this experiment.

The detectors consist of three massive imaging Čerenkov counters at 1, 3 and 20 km from the source. These detectors will have masses of 0.8, 0.8 and 6.3 kTons respectively. This experiment will be a ν_μ disappearance experiment using the quasi-elastic events as the signal. The raw event rate in the far detector is 18k per 100 days of running. The analysis will be performed by measuring the event rate in the far, intermediate and near detectors as a function of neutrino energy. Fig. 2 contains the exclusion plots for this experiment.

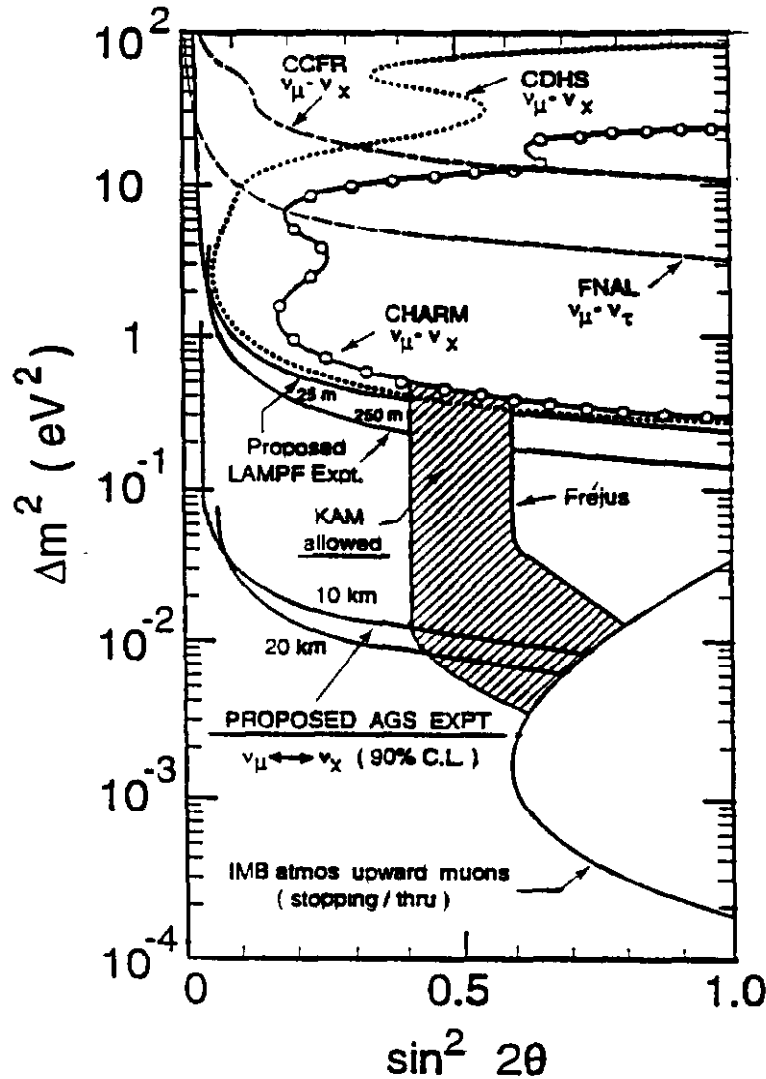


Figure 2: The regions accessible to the BNL-AGS experiment with the far detector at 10 km and 20 km.

4 CERN - Detector in Gran Sasso

The CERN-SPS is an 80 to 450 GeV proton accelerator which can conveniently be used to send a neutrino beam from CERN to the Gran Sasso Laboratory. The SPS-LHC transfer line is the the direction of Gran Sasso Laboratory and the distance of 730 km makes the beam a modest 3.3 degrees below the horizontal. The SPS accelerator is capable of delivering 10^{20} POT per 10^7 sec - year and the contamination of the muon neutrino beam from muon anti-neutrinos or electron neutrinos is at the per cent level. At 80 GeV the average energy of the neutrinos would be approximately 6 GeV.

The ICARUS detector[6] in the Gran Sasso tunnel would be a 5 kTon large liquid Argon TPC and that would have 4k charged current events per 10^{20} POT from the CERN neutrino beam. The $\nu_\mu \leftrightarrow \nu_e$ analysis would be based on ν_e appearance plus a precise understanding of the beam contamination and the backgrounds from ν_μ neutral current interactions with π^0 faking electrons. Whereas the results in the $\nu_\mu \leftrightarrow \nu_\tau$ mode would be based on a combination of analyses; ν_μ disappearance, the neutral current to charged current ratio, and direct appearance of ν_τ . The exclusion plots for the ICARUS/CERN experiment are given in Fig. 3.

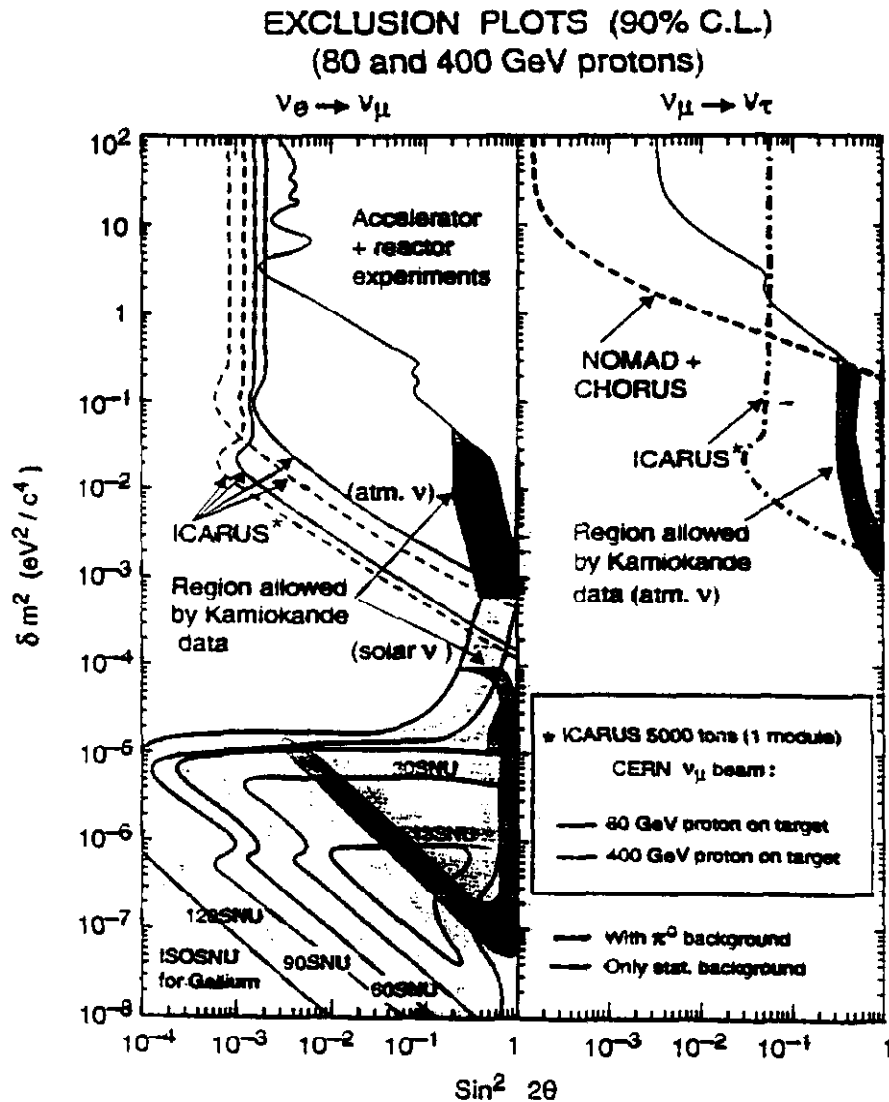


Figure 3: CERN/ICARUS exclusion plots for both $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$.

The GeNIUS (GeV Neutrino-Induced Underground Shower) [7] detector is a 17 kTon (15 kTon fiducial volume) fine-grained sampling calorimeter to be placed, if approved, in the Gran Sasso tunnel. With a neutrino beam similar to the FNAL beam from the Main Injector this detector would have 18k charged current events for 10^{20} POT. The analysis would be performed using the neutral current to charged current ratio for $\nu_\mu \leftrightarrow \nu_\tau$ and the electron-type to muon-type events for $\nu_\mu \leftrightarrow \nu_e$. The exclusion plots for this detector with the CERN-PS producing a neutrino beam with average energy of 5 GeV are given in Fig. 4.

CERN has also discussed the possibility of sending a neutrino beam, produced from 450 GeV protons, to SuperKamiokande, 9000 km away. The beam would have to be aimed 44 degrees below the horizontal. With such large separation between source and detector this experiment will be able to study matter enhanced oscillation effects in the $\nu_\mu \leftrightarrow \nu_e$ mode. An exclusion plot for this possibility can be found in Ref. [6].

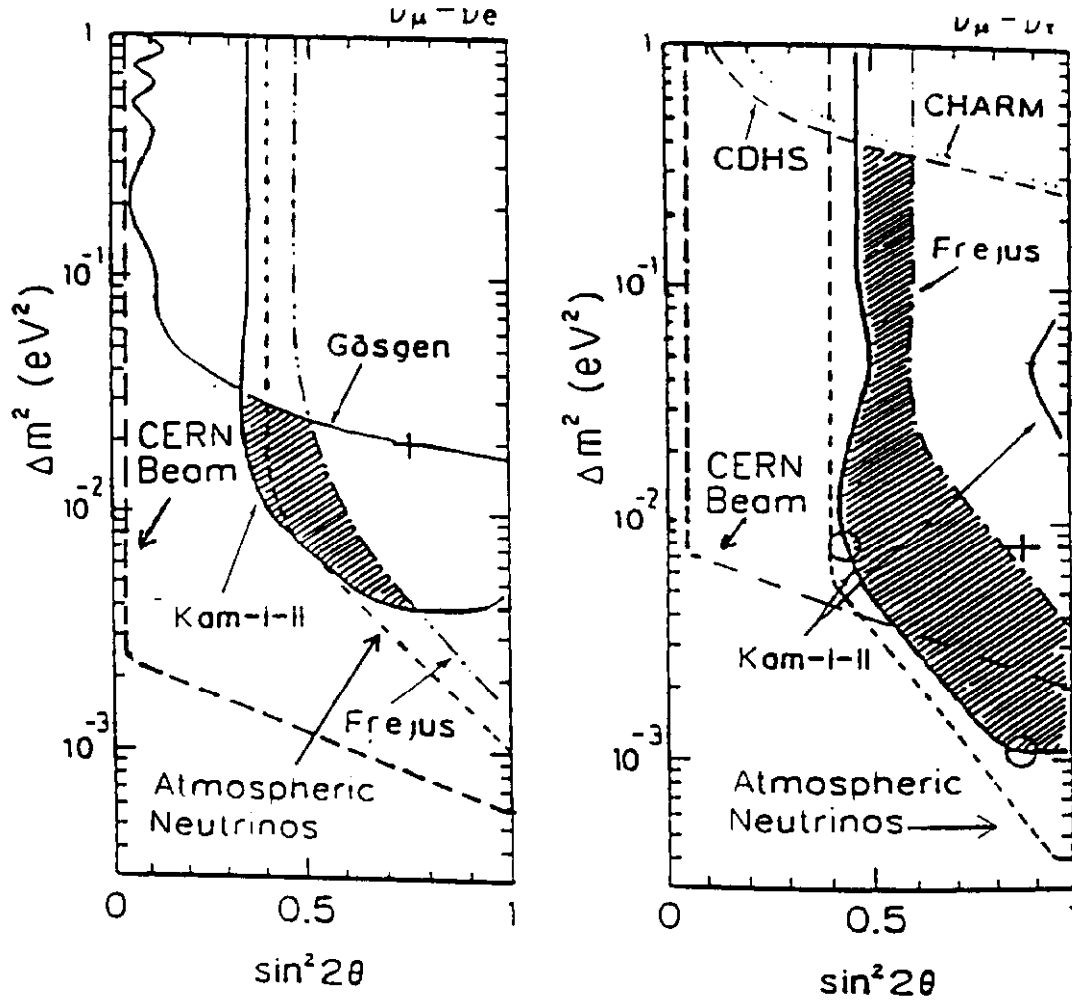


Figure 4: Area of oscillation parameter space ruled out at the 90% confidence level for one year of running for the GeNIUS detector and the CERN neutrino beam.

5 KEK - SuperKamiokande

The possibility of sending a muon neutrino beam the 250 km between SuperKamiokande and KEK has been discussed in detail by Nishikawa[5]. The KEK-PS is a 12 GeV proton accelerator which can currently deliver 4×10^{12} protons on target every 2.5 sec. Therefore a modest upgrade is required to the KEK-PS to deliver 10^{20} POT in a period of a few years. The average energy of the neutrino beam is approximately 1 GeV and the contamination of ν_e is a few percent.

SuperKamiokande is a 50 kTon water Čerenkov detector which is scheduled for completion in April of 1996. The event rate in the 20 kTons of fiducial volume of SuperKamiokande is 400 CC events for 10^{20} POT using a two radiation length target. The analysis for the $\nu_\mu \leftrightarrow \nu_\tau$ mode is based on the neutral current to charged current ratio for SuperKamiokande and a small water Čerenkov detector on the KEK site. This requires distinguishing an EM showering particle (e or γ) from a non-showering particle (μ or π) which can be attained with this detector above a few hundred MeV, whereas the $\nu_\mu \leftrightarrow \nu_e$ mode requires distinguishing between an electron and a π^0 which can be separated for neutrino energies greater than 2 GeV for this detector. The exclusion plots for this combination of accelerator and detector are given in Fig. 5.

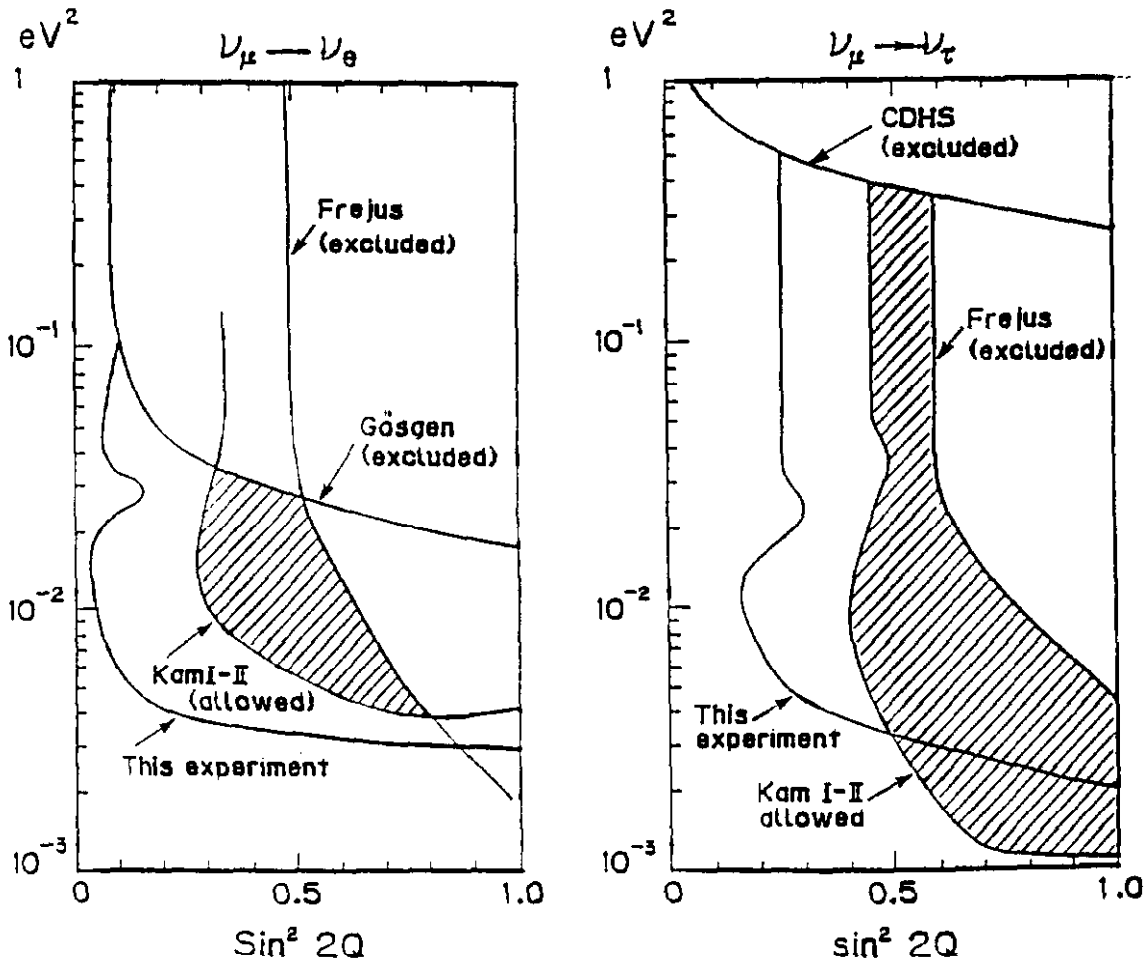


Figure 5: The 90% exclusion plots for the KEK-PS - SuperKamiokande experiment for both $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_e$.

6 Other and Conclusions

Another possibility is to use the proposed new accelerator at TRIUMF (KAON), aimed at either a new detector approximately 40 km from the source or to SuperKamiokande in Japan. Details of these possibilities are still under discussion. Using the SSC as a source of neutrinos has also been discussed in conjunction with GRANDE as a detector.

Given the results from the atmospheric neutrino data, it is important to explore the oscillation parameter region $10^{-3} \text{ eV}^2 < \Delta m_0^2 < 10^{-1} \text{ eV}^2$ and $\sin^2 2\theta_0 > 0.4$ [8]. Accelerator neutrinos are ideal for this purpose because the intense beams are well understood, with a more sharply peaked energy spectrum and can be manipulated as opposed to atmospheric neutrinos. There are a number of very exciting possibilities for experiments to explore this region of parameter space; let us hope that at least one of these experiments is actually performed. Remember that the fermion mass question is one of particle physics' great mysteries beyond the Standard Model, and any clues from neutrinos may unleash our imagination to further our understanding of nature.

7 Acknowledgements

I would like to thank R. Bernstein, M. Goodman, A. Mann, D. Michael, M. Murtagh, K. Nishikawa, J.-P. Revol and N. Weiss for providing me with many details for this review. Fermilab is operated by the Universities Research Association Inc. under contract with the United States Department of Energy.

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- [8] This region will be also explored by reactor neutrino oscillation experiments in the $\nu_\mu \leftrightarrow \nu_e$ mode. See other contributions to this workshop.